Joint Antenna-Channel Modelling for in-to-out-Body Propagation of Dairy Cows at 868 MHz

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***Abstract*—In this paper, for the first time, the in-to-out-body path loss between a capsule antenna placed inside the cows' rumen and a distant gateway was characterized at 868 MHz. Measurements were conducted on five different fistulated cows in a dairy barn. The in-body antenna gain was then de-embedded from the wireless channel. The difference between free space measurements and in-to-out-body path loss assessment was used to quantify the path loss increase due to the cows' body. Results have shown an increase of the path loss on average (all cows) by 50.6 dB, with a variation between 43.7 and 55.3 dB. The obtained results were used to calculate the range of a LoRa (Long range) based network accounting for the antenna channel. With an input transmit power of 14 dBm, ranges up to 175 m in indoor and 364 m in outdoor were obtained depending on the used bit rate.**

***Index Terms*—In-to-out-body path loss, cows, capsule antenna, internet-of-animals, link budget, propagation, radio channel**

I. Introduction

The size of dairy farms and the number of animals per stockperson are increasing. Within larger herds, timely detecting health problems of individual cows becomes a challenging and costly task. Monitoring health indicators in real time using sensors enables large dairy farms to optimize their profits as well as increase their cow welfare. Ruminal temperature and pH are important parameters to assess the nutritional and health status of dairy cows and to predict anomalies (e.g., metabolic disorders after calving) [1]. However, these parameters can be measured only using in-body sensors. In practice, for a real-time data collection, the in-body sensor would wirelessly transmit the measured data to a gateway. Therefore, the reliability of the in-to-out-body wireless communication is crucial for collecting such data.

Wireless Body Area Networks (WBANs) and Internet-of-Things (IoT) can be effectively used for health tracking of dairy cows to facilitate herd management and enhance cow welfare (IoA, Internet-of-Animals) [2]. Moreover, recent advances in low-power wireless communication technologies (e.g., Long Range (LoRa), Sigfox) working at 868 MHz allow long-range wireless communications and are scalable towards a large number of devices. Several studies have investigated the on- and off-body wireless communication for WBANs and IoT applications for animals [2], [3]. The in-to-out-body path loss has been characterised for cows at 433 MHz in previous work [4]. However, to the best of authors' knowledge, the in-to-out-body wireless link has not been investigated yet for dairy cows at 868 MHz. The aim of this study was to characterize the path loss between a transmitter placed inside a cow's rumen and a distant gateway at 868 MHz for different dairy cows accounting for the in-body antenna gains. Accurate link budget calculations will safeguard the reliability of the in-body-based monitoring system for dairy cattle.

II. Materials and Methods

A. Experimental environments and Animals

Measurements were conducted in a research barn at the Flanders Research Institute for Agricultural, Fisheries and Food (ILVO) in Melle, Belgium. In-to-out-body measurements were performed in a large area of about 6×18 m^2. Five different fistulated Holstein dairy cows (parity 2.8 ± 1.3) were used for the measurements. Fistulated cows are cows that have been surgically fitted with a cannula. A cannula acts as a porthole-like device that allows access to the rumen of a cow, to perform research and analysis of the digestive system. The cows were tied at a fixed position as shown in Fig. 1-a.

B. In-body capsule antenna

The design of the capsule antenna was presented in [5]. To characterize the radiation performance, the previously proposed approach [6] was used. The antenna was centered inside of a ∅100-mm spherical glass jar containing a muscle-equivalent phantom (the details of the experiment are provided in [5]). CST Microwave Studio 2018 [7] was used for the simulations. Detailed description of the numerical approach is given in [8].

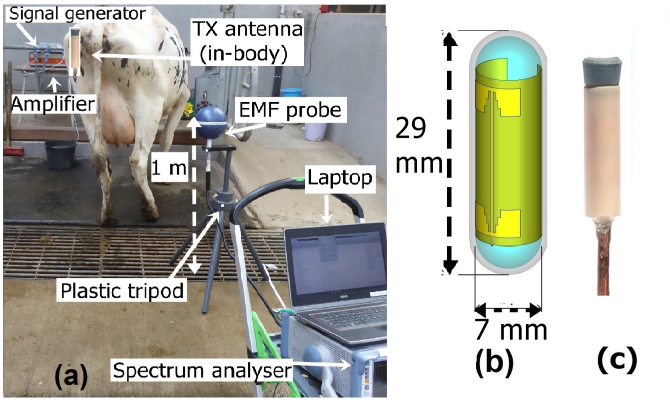

Fig. 1. (a) Measurement setup, (b) the capsule antenna designed for ingestible and implantable applications (see [5] for more details), and (c) The antenna after the preparation for the measurements

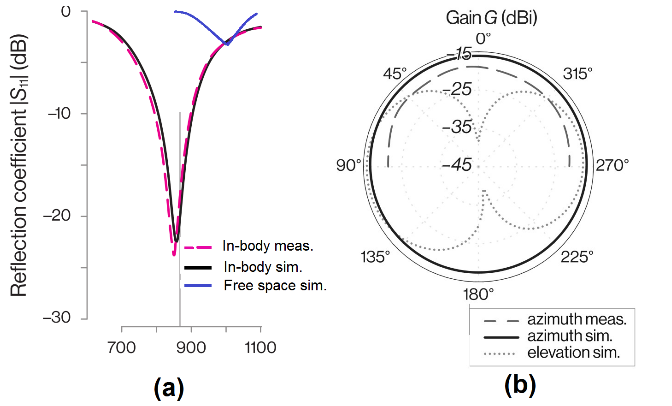

Fig. 2. (a) The reflection coefficient $|S_{11}|$ in free space and in a phantom (in-body) with muscle-equivalent EM properties. (b) In-body measured and computed radiation patters.

Fig. 2-a shows the impedance characteristics of the capsule antenna in the muscle-equivalent environment and in free space. The -10 dB bandwidth in the muscle-equivalent environment was 90 MHz (fractional BW=10%). The obtained bandwidth fully covers the relevant bands of wireless communication standards such as MedRadio, LoRa, Sigfox, etc. The $|S_{11}|$ in free space was -3.4 dB since the antenna was specifically designed for in-body applications.
To derive the antenna gain, the gain substitution technique was used. A reference antenna of a known gain [9] substituted the capsule antenna, and the measured gain of the reference antenna was used to calibrate the results. Fig. 2-b shows the far-field characterization results. The maximum measured gains G were -18 and -34.5 dBi for the in-body and free space, respectively. The radiation patterns and maximum gain values were consistent with the simulated ones. The low gain in free space is due to the strong mismatch in air ($|S_{11}| \approx -3.4$ dB) since the antenna was specifically designed for in-body applications and relies on dielectric loading by tissues to achieve higher impedance matching [10]. The presented values in this section were used for the antenna de-embedded path loss calculation (Section II-D).

C. Path loss measurements and scenarios

The setup of the path loss measurements is shown in Fig. 1-a. The transmitter part was composed of a transmitting antenna (TX) and a signal generator. As the TX, the capsule antenna described in [5] was used (Fig. 1-b, c). The TX antenna was placed in the rumen bottom of the fistulated cow and connected to an amplifier and a signal generator. The Rohde & Schwarz SMB100A (100 kHz-12.75 GHz) signal generator was used to inject a continuous wave signal at 868 MHz. The power at the output of the amplifier (injected to the antenna) was 32 dBm. The receiver part was composed of the EMF probe (Rohde & Schwarz TS-EMF, Italy) connected to a spectrum analyser and a laptop to store the data. The EMF probe was used to measure the three components of the received electric field. The measurements were carried out for different TX-RX separations (1 to 20 m). At each measurement location, 300 samples were recorded. The mean value of the samples was considered as a received power for the corresponding TX-RX separation. The measurements were performed also without cows. In this case, the TX antenna was mounted in free space at a height of 0.8 m (i.e., the distance from the bottom of the rumen to the ground). The measurements without cow were carried out to quantify the increase of path loss due to the cow body.

D. Joint antenna-channel:Path loss difference for body loss estimation

From the measured average received power P_{RX} (dBm) for a given TX-RX distance, the path loss $PL(dB)$ in free space (PL_{FS}) is calculated as follows:

$$PL_{FS} = P_{TX} + G_{TX_{FS}} - L_{TX} + G_{RX} - L_{RX} - P_{RX} \quad (1)$$

where P_{TX} is the transmitter power (dBm) (input power to the antenna), $G_{TX_{FS}}$ the TX antenna gain (dBi) in free space, L_{RX} the transmitter cable losses (dB), G_{RX} the receiver antenna gain (dBi), and L_{RX} the receiver cable losses (dB).

The definition of the path loss given by (1) cannot be applied directly to WBANs due to the inevitable interaction between the antennas and the cow's body. Because the antennas are positioned in the cow's body, their characteristics (e.g., gain) are influenced by the body. In this situation, the free space antenna gain cannot be used for calculating the in-to-out-body path loss. In literature [11], [12] the antenna gains are included in the WBAN path loss calculation given by (1). Thus, the path loss including the antenna gains as a part of the channel model (PL_{incl}) is calculated as follows:

$$PL_{incl} = P_{TX} - L_{TX} - L_{RX} - P_{RX} \quad (2)$$

However, with this approach, the obtained path loss models determined by simulations or measurements are specific for the used antenna type. To separate the antenna from the underlying channel, several new studies have tried to establish the so called *antenna de-embedding path loss* [13], [14], [15]. In this paper, the antenna gains provided in [5] are used for the path loss calculation instead of the free space gains. Thus, the path loss PL excluding the antenna gains (i.e., antenna de-embedded path loss) is given by:

$$PL_{body} = P_{TX} + G_{TX_b} - L_{TX} + G_{RX} - L_{RX} - P_{RX} \quad (3)$$

with G_{TX_b} is the *in-body* antenna gain of the TX antenna. Finally, the increase of the path loss $[PL(cow) - PL(without\ cow)]$ due to the cow body (i.e., body loss) for each individual cow is calculated as follows:

$$\delta_{PL} = PL_{body} - PL_{FS} \quad (4)$$

E. Link budget

In this Section, LoRa technology (Long Range) is proposed for in-body data collection for dairy cows accounting for the capsule antenna gains. A link budget is presented to calculate the network range. Table I lists the parameters used for the range calculation. Three bit rates are investigated (bandwidth 125 kHz, [16]): 0.25 kbps (min), 0.98 kbps (typical), and 5.47 kbps (max) (Table I).

TABLE I
Parameters used for the link budget calculation

Parameters	Value	Unit
TX power	14.0	dBm
TX antenna gain (in-body)	-18	dBi
SF	7; 10; 12	[-]
Bandwidth	125	kHz
Data rate	5.47;0.98;0.25	kbps
RX antenna gain (free space)	5	dBi
Sensitivity	-123;-132;-137	dBm

To determine the range, we firstly calculate the maximal path loss PL_{max}, to which a transmitted signal can be subjected while still being detectable at the receiver. The PL_{max} in dB is calculated as follows:

$$PL_{max} = P_{TX} + G_{TX} + G_{RX} - S_{RX} \quad (5)$$

In (5) , P_{TX} is the transmitter power in dBm, G_{TX} is the TX antenna gain in dBi, G_{RX} is the RX antenna gain, and S_{RX} is the receiver sensitivity in dBm. Next, the maximal path loss is compared to the distance-dependent path loss model including the body loss.

$$PL_d = PL_{d_0} + 10nlog(d/d_0) + M_s + M_f + Body\,Loss \quad (6)$$

with PL_d (dB) is the path loss at a distance d in m, PL_{d_0} in (dB) is the path loss at reference distance $d_0 = 1$ m, n the path loss exponent (-), d the separation distance between TX and RX in m, M_s the shadowing margin in dB, and M_f the fading margin in dB [17].
Finally, the range R in meter of the wireless system under consideration accounting for the body loss is the distance to the maximal path loss and can be determined by solving the following equation:

$$PL_{max} = PL_{d_0} + 10nlog(R/d_0) + M_s + M_f + Body\,Loss \quad (7)$$

Equation (7) can be solved for R using (6):

$$R = d_0.10^{(PL_{max} - M_s - M_f - Body\,Loss - PL_{d_0})/10n} \quad (8)$$

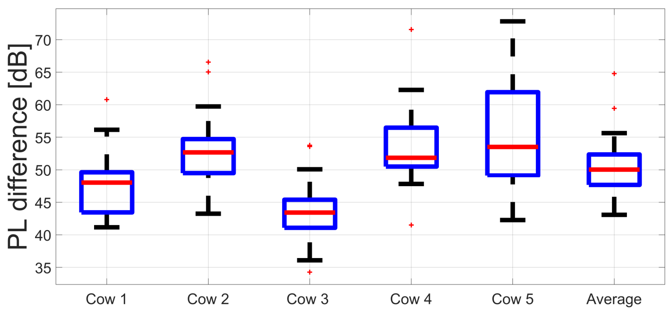

Fig. 3. Boxplot of the path loss (PL) increase due to the cow body for each individual cow and the average along all cows

III. Results and Discussion

1) Path loss difference: Figure 3 shows the increase of the path loss $[PL(cow) - PL(without\ cow)]$ at 868 MHz due to the cow body for each individual cow as well as the average along all cows. The mean value of the path loss difference varied between 43.7 dB (cow 3) and 55.3 dB (cow 5) with an average (all cows) of 50.6 dB (Table II). This variation was expected since the cows have different sizes and the quantity and type of feed in their rumen differ. The standard deviation between TX-RX locations varied from 4.8 to 8.4 dB, with an average of 4.8 dB for all cows. We note that these values quantify the real loss in power due to cow body (in-to-out-body antenna de-embedded path loss).

TABLE II
The mean, the median, and the standard deviation (SD) of the path loss difference for each individual cow and for all cows (Avg)

Cows	1	2	3	4	5	Avg
Mean (dB)	47.6	52.9	43.7	53.3	55.3	50.6
Median (dB)	48.0	52.7	43.4	51.8	53.5	50.0
SD (dB)	4.8	5.7	4.8	6.0	8.4	4.8

2) Network range: The path loss models obtained in previous studies [17] were considered (antenna de-embedded path loss models). The shadowing margin (M_s) was determined such that 95% of the locations at coverage cell edge are covered by the wireless system. This margin was derived from the standard deviation σ around the path loss model ($\sigma_{PLmodel}$) [17] and the standard deviation of the body loss ($\sigma_{Body\,loss}$) and equals 1.65σ, with $\sigma = \sqrt{\sigma^2_{PLmodel} + \sigma^2_{Body\,loss}}$. Fade margin ($M_f$) of 8 dB in indoor and 4 dB outdoor were considered for an outage probability of 0.01 (99% of the time, the variation around the median will not exceed the fade margin) [17].

The obtained ranges are listed in Table III. A maximum transmit power of 14 dBm was used. For the indoor scenario, the ranges were between 36 and 175 m. In outdoor (pasture), the ranges were higher and reach 364 m. In free space, LoRa provides higher ranges (10-19 km outdoor). This shows the

TABLE III
Parameters of the path loss models and the obtained ranges for the investigated scenarios

Scenarios		Indoor	Outdoor	Unit
Channel	$PL(d_0)$	38.6	33.3	dB
model	n	2.04	2.2	[-]
	M_s	5.2	5.6	dB
	M_f	8	4	dB
Body loss		50.6	50.6	dB
Range		36; 100; 175	78; 210; 364	m

high attenuation of the signal due to the cow body. The range could be extended by using lower bit rates, although this would limit the amount of collected data.

IV. Conclusion

The in-to-out-body path loss in dairy cows was characterised for the first time at 868 MHz. Based on the obtained results for five cows, the antenna de-embedded path loss increased on average by 50.6 dB, with a standard deviation of 4.8 dB. The obtained results were used to calculate the range of a LoRa based network accounting for the antenna channel. Ranges up to 175 m in indoor and 364 m in outdoor were obtained depending on the used bit rate.

Acknowledgment

This work was supported by the EOS project MULti-Service WIreless NETwork (MUSE-WINET). Margot Deruyck is a Post-Doctoral Fellow of the FWO-V (Research foundation Flanders, Belgium). The authors would like to thank Leen Vandaele and Sara Van Lembergen for their help during the measurements.

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